Appendix A

Pathways of Aquatic Species Introduction

An Initial Survey of Aquatic Invasive Species Issues in the Gulf of Mexico Region

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A.1 Introduction

A pathway, or vector, is the means by which a species enters an ecosystem. Pathways for nonindigenous species introductions (i.e., human-facilitated) can be divided into three categories: unintentional, intentional, and escape from confinement (Williams and Meffe 1998). As a generalization, most plant and vertebrate animal introductions have been intentional, whereas most invertebrate and microbe introductions have been unintentional (Pimentel et al. 1999). Table 1 presents the principal pathways of aquatic species introductions categorized by this scheme. This table includes pathways used for intentional beneficial introductions. These are included to understand the full range of pathways. In addition, the impacts of a nonindigenous species can change over time or as it enters new areas: some introductions that appear benign today may cause future harm (OTA 1993).

Table 1. Principal Pathways of Introduction for Aquatic Species

Pathway Category	Pathway of Introduction
Unintentional	• Transported Commodities • Vessels: Dry Ballast, Ballast Water, and Hull Fouling • Boat Trailers • Recreational Activities • Habitat Alteration / Canals • Interbasin Transfers of Water • Nontarget Species / Stock Contamination • Unknown
Intentional	• Agriculture, Horticulture, and Soil Conservation • Recreational Sport Fishing / Forage Species • Bait Bucket Releases • New Food Sources • Intentional Aquarium and Pet Releases • Biological Control • Species Conservation • Unknown
Escape from Confinement	• Horticulture • Ornamental Pond and Pet Escapes • Aquaculture and Fish Farms • Imported Live Food • Research / Public Display

Evaluating the relative importance of the many and varied pathways is complicated due to a number of factors. First, since time lags are common between actual introduction of an invasive species and subsequent establishment and detection, tracing the exact pathway is often difficult. For example, one estimate is that invasive weeds usually have to be in the U.S. for 30 years or

have spread to at least 10,000 acres before detection occurs (OTA 1993). Second, while federal port inspections provide valuable information on pathways (especially for agricultural pests), data are available only on whether species enter via specific routes, not on whether and how species enter via currently undetected routes. Finally, some comparisons between pathways defy quantitative analysis; for example, which is more important, the entry pathway of one very harmful invasive species or a pathway by which many less harmful species enter the U.S. (OTA 1993). For these reasons, this section does not attempt to rank the pathways by relative importance.

A.2 Unintentional Pathways

Transported Commodities

Many aquatic species enter the U.S. each year as unintentional contaminants of global trade. A variety of aquatic species can contaminate agricultural produce, nursery stock, cut flowers, and timber, and bulk commodities. At least 45 percent of the snails and slugs intercepted by agricultural inspectors between 1984 and 1991 were found on plants or plant products (OTA 1993). Transported commodities were the single greatest source of federal noxious weed interceptions from October 1987 through July 1990 (OTA 1993).

A considerable volume of transported freight is packed into standardized, boxcar-sized containers for ease of shipping and handling. This containerized freight is viewed as a significant pathway for the entry of insects, weed seeds, slugs, and snails into the U.S. (OTA 1993). Such containers can sit idle at ports for long periods of time, during which nonindigenous organisms can board. Usually containers are not cleaned between shipments. Inspecting containerized freight requires costly unloading and reloading of the contents. Consequently, inspections tend to occur only when there is good cause to suspect illegal imports or contamination by pests. Since containerized freight is frequently not unloaded until it reaches its inland destination, any nonindigenous species contained within are released inland rather than at a port of entry. This factor reverses the historical pattern wherein nonindigenous species generally first appeared at port of entry.

Similar to civilian commodities, military freight enters the U.S. continuously from all over the world. Vehicles, equipment, and supplies can contain soil or water from the field and can be an unintended source of weed seeds, insects, and plant pathogens. Several agricultural pests returned from Europe with military cargo and supplies following World War II (OTA 1993).

Vessels: Dry Ballast, Ballast Water, and Hull Fouling

Ballast is the material used to maintain stability and maneuverability when a vessel has little or no cargo on board. Solid or dry ballast, historically stone, sand, lead ingots, or practically anything that was available near shore, was used as nonpermanent ballast for sail or early steam ships. At the cargo loading port this material was removed, and stored or discarded. The appearance of certain nonindigenous organisms in the U.S., most notably species of plants and snails, has been attributed to this pathway (Dextrase and Coscarelli 2000).

The opportunity for transport and introduction of aquatic organisms increased greatly when ships began carrying ballast water instead of dry ballast. Ballast water, taken on by large cargo vessels when they are empty, is pumped out of ballast tanks when the ship is loaded at a different port. If environmental conditions are similar between ports, species in the ballast water from the first port may become established at the port where it is released. It was estimated in 1995 that transoceanic cargo vessels release over 2 million gallons of ballast water into U.S. waters every hour (Carlton et al. 1995).

For centuries, wooden sailing ships served as the main mode of global transportation and trade. During this time the most common form of unintentional transfer of aquatic organisms were those attached to or burrowed into the hulls of these ships (Benson 2000). Historical records exist about the great quantities of living material fouling the hulls of sailing ships: it was common practice to scrape off this mass, often many thousands of miles from where the ship originated (Benson 2000). Even through the materials used to construct hulls have changed, hull attachment continues to serve as a pathway for unintentional transfer across the globe.

Boat Trailers and Recreational Activities

Overland transport of boats on boat trailers is a common pathway for the unintentional introduction of nonindigenous aquatic species (OTA 1993). This would appear to be a significant pathway in the Gulf region, as warm weather makes year-round boating and fishing possible. In addition to boating and fishing, SCUBA diving, harvesting of bait, jet skiing, seaplanes, and waterfowl hunting serve as pathways. The U.S. Coast Guard is developing *Voluntary Guidelines on Recreational Activities To Control the Spread of Zebra Mussels and Other Aquatic Nuisance Species*, with guidelines for persons engaged in water-related recreational activities to help control the spread of aquatic invasive species.

Habitat Alteration / Canals

Man-made canals and diversions have facilitated the introduction of several fish species and probably some plants (Mills et al. 2000). The Tennessee-Tombigbee waterway and the extensive canal system in southern Florida serve as active canal pathways in the Gulf of Mexico region (Mills et al. 2000).

Interbasin Transfers of Water

One vector of special concern in the State of Texas is interbasin transfers of water (McKinney 2000). With water development infrastructure being constructed throughout Texas, the potential for rapid transfers of biota between river basins, and thus coastal bays, is increasing. The Texas Parks and Wildlife Department recently commissioned a study in an area where interbasin transfers will be likely, and found that risks were low for higher aquatic taxa (e.g., fish), but moderate for microbes and other lower taxa (McKinney 2000). This potential pathway exists in other parts of the Gulf of Mexico region, for example, the Tri-State Water Project for Alabama, Georgia, and Florida.

Nontarget Species / Stock Contamination

A tremendous array of fishes and other aquatic organisms have been introduced as "contaminants" or "by-products" associated with the intentional introduction of target species (Dextrase and Coscarelli 2000). Although these introductions are unintentional, they are integrally linked to intentional introductions. These introductions occur in several ways: accidental inclusion in transport containers, misidentification of species, transport in water or packing materials, or as parasites or pathogens in or on the target organism. A number of fish and shrimp pathogens and parasites have entered the U.S. in infected stock for aquaculture, commercial processing, or fisheries enhancement (OTA 1993). Fish imported into the aquarium trade can harbor parasites: one 1984 study of hundreds of fish shipped from Southeast Asia and South America found infestation rates from 61 to 98 percent (OTA 1993).

Baitfish harvesting processes may also lead to baitfish species being introduced to new waterbodies. When multiple sites are harvested, species caught at one harvesting site might be inadvertently released at the next harvesting sight. Harvesters also may remove non-target fish species from their catch while traveling between sites and release them into non-native waters.

A.3 Intentional Pathways

For centuries nonindigenous species have been intentionally introduced to support agriculture, landscaping, soil stabilization, recreational fishing, bait production, and aquaculture. Many of these introductions have improved the quality of our lives and sustain significant sectors of the world's economy. Intentional introductions are conducted with a specific purpose and presumably with some forethought into the likely success (and potential impacts) of the introduced organisms (Dextrase and Coscarelli 2000). However, history has demonstrated unintended consequences. As discussed above, intentional introductions can also result in unintentional introductions of nontarget species.

Agriculture, Horticulture, and Soil Conservation

Nonindigenous plants are used extensively for agriculture and horticulture in the U.S.; related industries generate a large portion of the U.S. Gross National Product. Many horticultural plants are introduced for aesthetic reasons, and numerous terrestrial and aquatic species are widely available at nurseries, garden centers, and seed distributors. Other nonindigenous plants are introduced for ecological reasons. For example, melaleuca (*Melaleuca quinquenervia*), a highly invasive tree, was planted in southern Florida to dry out wetland areas (McCann et al. 1996). Kudzu (*Pueraria lobata*), another highly invasive species, was initially introduced for soil conservation purposes.

Although the majority of nonindigenous plant introductions are legal, others occur illegally. Some seeds are sent to plant breeders in the U.S. through international first-class mail to avoid inspection or quarantine at the port of entry (OTA 1993). More than 80 percent of the nonindigenous plants and noxious weed seeds intercepted at U.S. ports of entry between October 1987 and July 1990 occurred in the baggage of international travelers (OTA 1993). Asian

waterspinach (*Ipomoea aquatica*) is a federal noxious weed and a prohibited aquatic weed in the State of Florida. However, from 1979 through 1990, Florida officials recorded 20 cases of illegal possession of seeds or deliberate plantings (OTA 1993).

Intentional Fish and Shellfish Introductions

There is a long history of intentional fish and shellfish introductions in the U.S., including both exotic species and native transplants. Large-scale, government-sponsored fish stocking for recreational fishing purposes began in the late 1800s. Such stocking programs are less common today, but continue still. For example, the State of Texas tried unsuccessfully to introduce the Nile perch (*Lates niloticus*) and bigeye lates (*Lates mariae*) in 1979 and 1983, respectively (Fuller et al. 1999).

Extensive commercial networks that sell and ship nonindigenous species are common in the U.S. For example, various organisms such as water fleas, freshwater shrimp, crayfish, freshwater clams, turtles, and bull frogs, are available through the mail for wildlife enhancement nationwide (OTA 1993). Whether these species are nonindigenous in some regions where they are marketed and sold is impossible to track, since species names are not always listed (OTA 1993).

Recreational Sport Fishing

Nearly one-half of the nonindigenous freshwater fishes that have been intentionally introduced in North America were released to establish sport fisheries and to diversify angling opportunities (Fuller et al. 1999, Crossman and Cudmore 2000). Sport fishes are introduced to address a number of recreational issues – absence of sport fish species in a particular water body, demand to introduce more desirable and familiar sport species, and introduction of hardier species when native habitats become unsuitable for indigenous species. Stock contamination and stock misidentification has caused unintended species releases.

Forage Species

To compensate for potential inadequacies in the natural food supply for introduced sport fishes – both native and non-native – forage fishes and other prey species (e.g., mysid shrimp) have been introduced into numerous U.S. lakes, reservoirs, and rivers since the 1950s (Dextrase and Coscarelli 2000).

Baitfish Production

Commercial baitfish harvesters have “seeded” ponds and small lakes with nonindigenous baitfish species to create a population that can be regularly, and often exclusively, harvested (Litvak and Mandrak 2000).

Bait Bucket Releases

Bait buckets have served as an active pathway for fish introductions for much of U.S history. More recent introductions of baitfish can be attributed to many newly developed sport fisheries (Litvak and Mandrak 2000). Many anglers dump bait buckets at the end of the day as a way of disposing of bait or with the assumption that it will become food for sport fish (Benson 2000). It is estimated that 109 fish species have been introduced to U.S. waters through bait-bucket

releases (Litvak and Mandrak 2000). Nonindigenous salamanders and crayfish have also been released as unused bait (Fuller et al. 1999).

New Food Sources

Both fish and shellfish have been intentionally introduced to provide new food sources and occasionally to develop commercial fisheries (Dextrase and Coscarelli 2000). Nonindigenous clams and oysters have been intentionally imported and released in U.S. waters for commercial exploitation (OTA 1993).

Intentional Aquaria and Pet Releases

Given the high volume of U.S. pet imports – estimated to be hundreds of thousands to millions of wild birds, aquarium fish, and reptiles annually – the potential exists for both intentional releases of unwanted plants and animals and unintentional pet escapes (OTA 1993). Illegal imports further expand the total numbers and types of organisms brought into the country.

Both individual aquarium hobbyists and commercial aquarium operations have been the intentional source of several nonindigenous aquatic species now established as reproducing populations in U.S. waters (Crossman and Cudmore 2000). Many intentional introductions occur when individual aquarium and ornamental pond keepers release their fish once they are too large or too numerous to be maintained (Benson 2000). In addition, several freshwater fish species have been introduced by immigrants trying to recreate the ambiance of their home countries (Dextrase and Coscarelli 2000).

Biological Control

Biological control is often viewed as an inexpensive and environmentally safe way to control invasive species, especially when compared to mechanical control and pesticides. Intentional release of biological control organisms has been, and continues to be, a source of nonindigenous insects, snails, fish, plant pathogens, and nematodes in the U.S. It is estimated that a total of 722 nonindigenous insect species have been purposely introduced in the U.S. for biological control purposes; of these, 237 have become established (OTA 1993).

The success of insects as biological control agents has encouraged the use of fishes for this purpose (Dextrase and Coscarelli 2000). Some predator fish species have been intentionally introduced to reduce numbers of overpopulated prey fish while simultaneously providing sport fisheries (Dextrase and Coscarelli 2000). While usually well researched prior to release, biological control introductions can still have unintended consequences. The grass carp (*Ctenopharyngodon idella*), an Asian fish, was introduced into the Gulf of Mexico region for the purpose of vegetation control, however, it has concurrently destroyed habitat for native freshwater fishes. Worldwide, biological control agents have been implicated in the extinction of almost 100 animal species (Dextrase and Coscarelli 2000).

Species Conservation

Introductions of nonindigenous species for conservation purposes are conducted to provide a refuge for species that are threatened with extinction in their native habitats. Such efforts have usually resulted in introductions into refuges near native areas or waters with the endpoint of reintroduction into native habitats when they become suitable (Dextrase and Coscarelli 2000), usually as part of a formal recovery plan.

A.4 Escape from Confinement Pathways

Another form of introduction occurs when a nonindigenous species, intentionally imported and/or cultured in human control and confinement, accidentally escapes. Escape of aquatic species can occur from research facilities, public aquaria, aquaculture facilities, ornamental fish farms, aquaria supply centers and pet stores, ornamental ponds, etc. How this category of pathways differs from intentional and unintentional pathways is that often the associated operation is licensed and/or permitted to import, maintain, distribute, or sell the species in question. The obvious exception is escape of ornamentals and pets from private citizens.

Aquaculture and Ornamental Fish Farms

Each year more than $170 million of nonindigenous tropical fishes and aquarium plants are imported into Florida (OTA 1993). Fish farms are the source of at least 27 nonindigenous fish species now established in the continental U.S. (OTA 1993), and a source of the several tropical aquarium species now found in Florida's waters (McCann et al. 1996, Fuller et al. 1999). However, given the large number of species cultivated and the large number of producers involved, established populations of fishes resulting from escapes from ornamental fish farms are rare (Hill 2001).

Aquaculture species, such as fish and shrimp, can escape from confinement due to improper screening of the outfall, high water events that flood facilities, and birds that transport and drop organisms outside of the confined area. For the aquaculture industry, increased awareness about the harmful effects on invasive species have resulted in management practices, both mandated and volunteer, that greatly reduce the probability of any single species escaping and becoming established in the new ecosystem.

Research and Public Display

Several nonindigenous species imported for medical diagnostic or research purposes have escaped from research facilities (OTA 1993). Pike killifish (*Belonesox belizanus*) were released in Florida after laboratory experiments at the University of Miami (P. Fuller, pers. comm.).

Ornamental Pond and Pet Escapes

Ornamental fish ponds are often stocked with nonindigenous species, for example goldfish (*Carassius auratus*) and water hyacinths (*Eichhornia crassipes*). While infrequent, these ponds can flood and/or fail, introducing species to the surrounding ecosystem.

A.5 Factors Affecting Pathways and Rates of Introduction

Changes to Native Habitat

Changes or alterations in natural habitat create opportunities that are beneficial to the establishment of both terrestrial and aquatic nonindigenous species. The majority of these habitat changes are the result of or influenced by human activities, and include the following general modifications:

- *Soil disturbances* from construction and agriculture provide an environment conducive to colonization by nonindigenous plants, including many species of weeds. These plants may then provide ideal habitat for nonindigenous insects that evolved with them.
- *Irrigation of arid regions* provides new habitat for species that normally do not tolerate dry conditions.
- *Fire frequency*.
- *Grazing intensity*.
- *Changes in nutrient levels*.
- *Thermal effluents* from power stations and industries create new habitat for tropical nonindigenous species.
- *Pollution and degradation* make some environments inhospitable for indigenous species, causing natural resource managers to introduce nonindigenous species that are more tolerant of the degraded conditions (OTA 1993).

Human changes to natural environments can span large geographical areas and can provide effective conduits for species movement between previously isolated locations. Large-scale modifications, such as railways, highways, roads, backcountry trails, irrigation systems, and water canals, play an important role in facilitating the spread of nonindigenous species.

Technological, Social, and Political Factors

This section was adapted from OTA 1993.

Pathways and rates of species introductions to the U.S. are influenced by technological innovations and social and political factors (Table 2). Many pathways that were significant sources of nonindigenous species in the past have either declined in importance or ceased to function. Such pathways, nevertheless, frequently are mentioned in discussions of nonindigenous species and can confuse attempts to identify current problems.

Some technological innovations enhance introduction rates. For example, the advent of commercial air traffic in the 1930s greatly facilitated the transport of small birds and fish that previously had been difficult to keep alive and healthy on longer voyages. It had a similar effect on the successful number of insect introductions for biological control. Other new technologies have slowed introduction rates. Many important weeds entered and spread throughout the U.S. as contaminants of agricultural seed in the 1700s and 1800s. Improvements in threshing and harvesting machinery beginning in the 1800s decreased seed contamination.

Table 2. Factors Affecting Species Movements

Illustrative Technological Innovations

Innovation	Effect
Switch from dry to wet ballast in 1800s	Changed from transport of insects, seeds, and plant pathogens to transport of fish and invertebrates
Increased rate of transit via steam ships and airplanes	Increased survival of insects, mammals, birds, and fish during transfer; increased success of introductions
Improvements in threshing and harvesting machinery	Decreased contamination of seed lots and entry and spread of weeds
Styrofoam coolers	Increased number of fish species amenable to transfer and their survival
Containerized shipping of freight	Created new mechanism for unintentional transfer of plant, insect, snail, and slug species; direct rout to country interior (i.e., away from shipping port)
Importation of used tires for retreading	Created new pathway for entry of mosquitoes

Illustrative Social and Political Factors

Social or Political Factor	Effect
New patterns of immigration and tourism	Change pathways for spread of species
Wars and military movements	Create new pathways for species spread
Globalization of trade	Create new pathways for species spread
Free trade agreements	Increase opportunity for species entry
Increased interest in exotic pets	Affect kind and number of species imported in the pet trade
Continued interest in new ornamental plants	Provide incentive for continued plant exploration and importation

Source: OTA 1993

Changing fashions in species preferences can drive importation, especially of organisms valued for their aesthetic qualities. Rates of introduction of aquatic snails accelerated during the 1970s, apparently because of expansion of the aquarium trade and renewed interest in freshwater aquaculture. Some preferences relate to patterns of human immigration.

Political and economic factors are also significant. The location and size of military actions determine their potential for species transfer. State and federal plant quarantine laws slowed rates of introduction of insect pests and plant pathogens after 1912. A reversal of this trend for

plant pathogens after 1970 may relate to globalization of agriculture and increased plant imports. The Federal Seed Act diminished the flow of weed species into the U.S. that previously had entered as seed contaminants.

Actions of interested constituencies can have an effect insofar as they influence laws and regulations restricting species flow. Conferences, position statements, and other activities of the American Fisheries Society since 1969 helped motivate states to regulate releases of nonindigenous fish. Conversely, effective lobbying by the Pet Industry Joint Advisory Council helped halt federal efforts to tighten regulation of fish and wildlife imports during the 1970s.

Finally, the magnitude of opportunity plays a role in introductions. As the shipping industry has grown in specific regions, so too has the number of nonindigenous species introductions. Construction of roads into new areas similarly increases the opportunity for species movement and urbanization contributes to an increase in the establishment of nonindigenous plants.

A.6 The Spread of Invasive Species

Invasive species can spread after becoming established in a new ecosystem. For such species, the pathways of spread within the U.S. become important from a management or regulatory perspective. Most invasive species spread within the U.S. via pathways associated with human activities. Many of these are the same pathways that bring new species into the country, like ballast water, while others are unique to the domestic movement of species, like boats and boat trailers used at multiple waterbodies. A number of the domestic pathways are linked to national distribution systems that enable an invasive species to become widely disseminated and introduced many times throughout the country. Multiple introductions speed dispersal and have significant consequences for the choice of appropriate management strategies.

Unassisted Spread

Established invasive species can disperse in the absence of human facilitated transference. For example, few geographic barriers block transcontinental expansion for species like the Asian tiger mosquito (*Aedes albopictus*). Wind and water can disperse a nonindigenous plant's seeds, and plants like the Brazilian pepper tree (*Schinus terebinthifolius*) in Florida have been spread by wildlife that consume the tree's seeds (OTA 1993). For mobile aquatic species, rivers and the natural connections between lakes serve as the principle pathways of spread. Striped bass introduced to the Sacramento River spread from southern California to Alaska (P. Fuller, pers. comm.) A nonindigenous fish introduced to the Mississippi River, or one of its tributaries, could theoretically spread to two-thirds of the U.S. Man-made canals provide an aquatic route where one would not naturally exist. The range of certain fish parasites has expanded as infected fish have migrated within and between watersheds (OTA 1993).

Natural disasters have provided new opportunities for the establishment of nonindigenous species. For example, Hurricane Andrew, passing over southern Florida in 1992, knocked down indigenous trees, which spurred the growth of nonindigenous vines in some natural areas; state

officials fear such an opportunity may result in permanent domination of certain indigenous plant communities by nonindigenous species (OTA 1993).

Assisted (Unintentional and Unintentional) Spread

Similar to internationally-transported commodities, domestic shipments of plants and animals, bulk cargo, and manufactured products have harbored invasive species (OTA 1993), even though interstate trade in agricultural products is often subject to domestic quarantines by the U.S. Department of Agriculture. Both government-sponsored and illegal releases of fish and shellfish for recreational purposes have increased the range of invasive species

The Effect of Global Climate Change on the Spread of Nonindigenous Species

The predicted warming trends associated with global climate change adds greatly to the complexity of defining and managing invasive species. It is predicted that increases in atmospheric temperature would allow established species to extend their ranges northward across the United States. The thermal structure in aquatic environments will follow the trend in atmospheric temperatures, providing opportunities for species to invade North America from Central and South America, and other warmer regions (Leach 2000). Incidences of diseases and parasites could also increase as vector organisms extend their ranges (Leach 2000).